Conclusion

With the proper skin coating, the attainment of temperatures below 250°K in a small satellite appears feasible if the ratio of internally-dissipated power to skin area is not excessive. In such a small "cool" satellite, components which require higher temperatures for proper operation must be in good thermal contact with heat-dissipating components, with relatively high thermal resistance between them and the skin.

If a larger satellite's orbit and attitude are such that an isolated section of its skin receives no radiation from the earth or sun, it might be possible to refrigerate a few components passively to temperatures as low as 150°K, keeping heat-dissipating components (and components which require higher temperatures) in contact with warmer skin sections. However, in addition to the obvious difficulties inherent in the attainment of such an orientation of the satellite, there will be problems in achieving structural strength while maintaining high thermal resistance between the refrigerated compartment and the remainder of the satellite's volume. Strengthening members will constitute thermal leaks through the insulation. Also, low thermal resistance in the conducting bar and radiator are to a certain degree incompatible with light weight.

Nevertheless, it may be feasible to maintain some electronic components and subassemblies in a satellite at temperatures below 250°K, so the possibility of taking advantage of these lower temperatures should be considered by designers of electronic equipment.

Extra-Terrestrial Radio Tracking and Communication*

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Summary—When the U. S. Army lunar program was initiated in 1958, the Jet Propulsion Laboratory (JPL) was assigned the responsibility for the upper rocket stages and the payload. Payload responsibility included radio tracking and communication with the lunar probe.

JPL's Microlock system, used for communicating with the early Explorer satellites, did not have sufficient range to perform this mission. Therefore, a new radio system designated TRAC(E) (TRacking And Communication, Extra-terrestrial) was designed. To the best knowledge of the authors, the TRAC(E) system is the first deep-space communication link to provide accurate tracking and telemetry data at lunar distances.

The design principles of the TRAC(E) system are presented in this paper in conjunction with a description of the equipment and actual performance data taken during the Pioneer IV lunar mission in March, 1959. The TRAC(E) system is an integral part of the NASA-JPL radio tracking station located near Goldstone Lake north of Barstow, Calif.

Future plans for improving the performance of the TRAC(E) system are indicated.

* Original manuscript received by the IRE, December 2, 1959. Portions of this paper were originated under studies conducted for the Dept. of Army Ordnance Corps under Contract No. DA-04-495-Ord-18. Such studies are now conducted for the Natl. Aeronautics and Space Administration under Contract No. NAS w-6.

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I. Introduction

The TRAC(E) system is a versatile space communications system which is capable of simultaneous tracking and communication with earth satellites, lunar vehicles, or space probes. Two major questions which had to be answered in the design of such a communication system for extreme range applications were: What is the operating frequency? What is the size of the ground antenna? The ground antenna is considered in a separate report.[1] The factors which determined the operating frequency of the TRAC(E) system are outlined herein.

The transmitter in the space probe produces a signal power (P_t) limited by the efficiency of the transmitter and the weight of the vehicle electrical power supply. This power is beamed in the direction of the Earth-based receiver to provide an effective gain (G_t) of the signal power relative to radiation uniformly into space. The amount of beaming that can be realized is limited by the accuracy with which the vehicle's antenna can

[1] K. W. Linnes, W. D. Merrick, and R. Stevens, "Ground antennas for space communication systems," IRE Trans. on Space Electronics and Telemetry, vol. SET-6, pp. 45–54; March, 1960.

be pointed and/or its attitude controlled. Since the feasibility of vehicle-borne directional antennas for space communications has not yet been demonstrated, present vehicle antennas are gain-limited. Therefore, the signal power (P_r) received by an Earth-based station is given by

$$P_r = P_t G_t A_r \left(\frac{1}{4\pi R^2}\right). \tag{1}$$

The term R represents the distance between the space vehicle and the Earth-based station. The Earth-based antenna is assumed to be area-limited.[1] Examination of (1) reveals that the received power is independent of frequency, to a first order at least.

The choice of the operating frequency can be narrowed somewhat by choosing frequencies which are not seriously affected by the ionosphere (above 100 mc) nor by the atmosphere (below about 10,000 mc). With regard to interference, virtually every known source of radio interference decreases with increasing frequency. Of particular importance to space communications is the decrease in brightness temperature of the galaxy with frequency. The largest source of galactic interference lies along the Milky Way or galactic center in the band approximately 15 degrees wide lying near the possible destination and orbits of space vehicles. Reduction in this interference can be accomplished by using antennas with relatively narrow beamwidths and operating at the highest frequency that is practical.

In view of the factors considered above, the optimum communication frequency was actually determined by such factors as vehicle transmitter efficiency and ground receiver sensitivity, that is, state-of-the-art considerations. Within the time scale of the U. S. Army Lunar Program (which was subsequently transferred to NASA) and the weight limitations of the Pioneers III and IV Lunar probes, development of an efficient stable transmitter in the 1000-mc range appeared feasible. An operating frequency of 960.05 mc was eventually chosen.

The design of the TRAC(E) system is based upon phase-lock techniques which have been under continuing investigation and development at the Jet Propulsion Laboratory (JPL) since 1953.[2-6] The technique, used by JPL in the Microlock system,[6] permits use of receiver bandwidths significantly smaller than the Doppler shift expected from space vehicles and proper addition of a limiter provides near-optimum performance over a wide dynamic range of both signal and interference levels.[3] Action of the VCO is such that with proper design, the Doppler component is effectively removed at the first mixer which permits narrow-band predetection amplification. Telemetry subcarriers are synchronously detected, and the information is available at the output of the phase-locked FM discriminators.

II. TRAC(E) System for Pioneers III and IV

Fig. 1 is a functional block diagram showing the TRAC(E) system as it was originally designed for tracking and communicating with the Pioneers III and IV probes. In the probe transmitter, the 40.0021-mc crystal-controlled oscillator signal is phase modulated with telemetry subcarriers which contain the measured data as frequency modulation. The resultant phase-modulated signal is frequency multiplied by a factor of 24 and amplified to provide a 960.05-mc signal to the probe antenna. The transmitter signal output, normalized to unity, is

$$\text{Cos}\,[24\omega_c t + s(t)] \tag{2}$$

where $s(t)$ is the composite phase modulation signal.

The TRAC(E) receiver is a narrow-band phase-coherent double-conversion superheterodyne receiver which employs three balanced mixers at 960 mc, three balanced detectors at 30 mc, and four synchronous detectors at 455 kc. The mixers and detectors are three terminal devices having an input, a coherent reference and an output, and they perform the analytic function of multiplying the waveform of the input signal by the waveform of the reference. These devices in conjunction with three 30-mc IF preamplifiers, three 455-kc IF amplifiers, and the voltage-controlled local oscillator comprise the major portion of the ground receiving system. They are arranged in such a manner as to function as the differencing elements of four highly accurate servo systems: 1) the RF servoloop at 960 mc, 2) the AGC loop, 3) the declination servomechanism, and 4) the hour angle servomechanism.

The received signal is

$$A(t)\cos\,[24(\omega_c t - \phi_c) + s(t)], \tag{3}$$

where $A(t)$ is the signal amplitude factor of the space-to-earth signal at the ground station and

$$\phi_c = \frac{\omega_c}{c}\int_0^t \dot{R}\,dt,$$

radians, the Doppler shift on ω_c. The significant waveform equations for the TRAC(E) receiving system are listed in Table I. The numeral preceding each expression refers to the corresponding numerals in Fig. 1.

The system parameters which were used to achieve

[1] E. Rechtin, "The Design of Optimum Linear Systems," Jet Propulsion Lab., California Institute of Technology, Pasadena, External Publication No. 204; April, 1953.

[2] R. Jaffe and E. Rechtin, "Design and performance of phase-lock circuits capable of near optimum performance over a wide range of input signal and noise levels," IRE Trans. on Information Theory, vol. IT-1, pp. 66–76; March, 1955.

[4] C. E. Gilchriest, "Application of the phase-locked loop to telemetry as a discriminator or tracking filter," IRE Trans. on Telemetry and Remote Control, vol. TRC-4, pp. 20–35; June, 1958.

[5] S. G. Margolis, "The response of a phase-locked loop to a sinusoid plus noise," IRE Trans. on Information Theory, vol. IT-3, pp. 136–144; March, 1957.

[6] H. L. Richter, R. Stevens, and W. F. Sampson, "A Minimum Weight Instrumentation System for a Satellite," Jet Propulsion Laboratory, California Institute of Technology, Pasadena, External Publication No. 376; May 23, 1957.

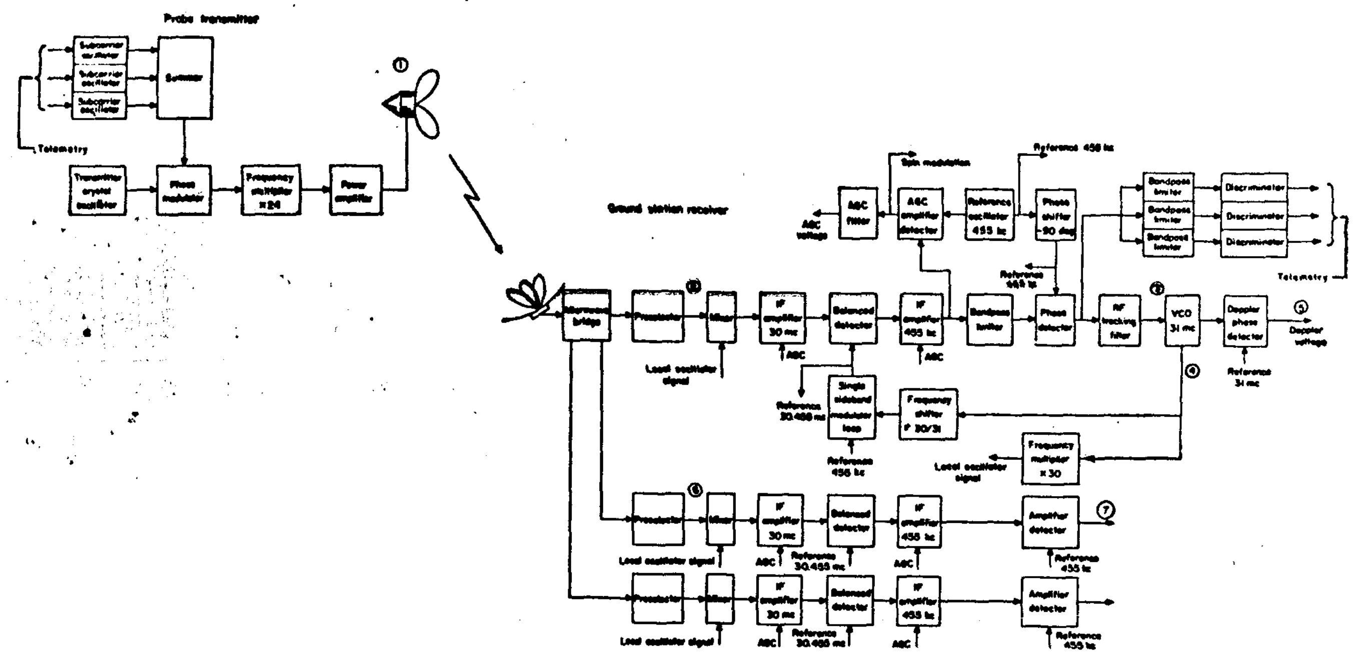


Fig. 1—Functional block diagram of the Pioneer IV transmitter and the Goldstone TRAC(E) System.

TABLE I
WAVEFORM EQUATIONS USED IN TRAC(E) SYSTEM

(1)	$A(t)\cos\left[24\omega_c t+s(t)\right]$
(2)	$g_\Sigma(\alpha)A(t)\cos\left[24(\omega_c t-\phi_c)+s(t)\right]$
(3)	$\sin 24(\phi_c^*-\phi_c)\approx 24(\phi_c^*-\phi_c)$
(4)	$\cos\dfrac{31\times 3}{30\times 4}(\omega_c t-\phi_c^*)$
(5)	$\cos\dfrac{31\times 3}{30\times 4}\phi_c^*=\cos\left[\dfrac{31\times 3}{30\times 4}\right]\dfrac{\omega_c}{c}\displaystyle\int_0^t \dot{R}\,dt$
(6)	$g_\Delta(\alpha)A(t)\cos\left[24(\omega_c t-\phi_c)+s(t)\right]$
(7)	$E\dfrac{A(t)}{A^*(t)}\dfrac{g_\Delta(\alpha)}{g_\Sigma(\alpha)}\approx\dfrac{A(t)}{A^*(t)}g_\Delta'(0)$

$A(t)$ = signal amplitude factor of the signal radiated from the probe
E = dc reference in the receiver AGC loop
c = velocity of propagation, meters/second
f_1 = measured frequency of the 31-mc Doppler reference
f_{c_0} = probe transmitter oscillator frequency with zero Doppler
f_d = measured frequency at the output of the Doppler phase detector
$g_\Sigma(\alpha)$ = voltage pattern of the main-beam antenna normalized so that $g_\Sigma(0)=1$
$g_\Delta(\alpha)$ = voltage pattern of the split-beam antenna normalized with respect to $g_\Sigma(0)$
$g_\Delta'(0)$ = slope of the $g_\Delta(\alpha)$ curve near $\alpha=0$, mils^{-1}
$s(t)$ = telemetry phase modulation
t = time, seconds
$\dot{R}$ = radial component of probe velocity meters/second

$$=c\left[1-\frac{960}{31 f_c}(f_d+f_1)\right]$$

α = tracking error of the antenna servo, mils
ϕ_c = Doppler phase shift on $\omega_c=\dfrac{\omega_c}{c}\displaystyle\int_0^t \dot{R}\,dt$, radians
ω_c = angular frequency of the probe transmitter oscillator $=2\pi(40.0021$ mc) radian/second
$\dfrac{1}{A^*(t)}$ = a measure of the voltage gain of the ground receiver so defined that the incoming signal $A(t)$ multiplied by the receiver gain figure $1/A^*(t)$ equals unity

accurate tracking and communication with the Pioneer IV probe to lunar distances and farther are listed in Table II. The 180 mw of transmitter power (± 0.5-db power tolerance) was distributed between the carrier (96 mw) and the three telemetry carriers so that accurate tracking and reliable data transmission could be realized to at least 250,000 miles (lunar distance). Tolerances shown on the carrier (± 0.3 db) and telemetry subcarriers (± 0.5 db) apply to permissible variations in phase modulation index ($\pm 2°$ on each subcarrier). Examination of Table II shows that with the lunar probe at a range of 250,000 miles, the received carrier signal level is -141.1 dbm (decibels referred to one milliwatt). The resultant signal-to-noise ratios (S/N) in the RF loop, AGC loop, and angle tracking loop are 8, 39.7, and 38.2 db, respectively. This provided sufficient margin in signal level to insure successful tracking and communication. The significance of the bandwidths of the RF loop, AGC loop, and angle tracking loop shown in Table II is discussed later.

TABLE II

TRAC(E) SYSTEM CHARACTERISTICS FOR PIONEERS III AND IV

Transmitter Power, Total (at 250,000 miles)	180 mw±20 mw(+22.5 dbm ±0.5 db)
Vehicle Antenna Gain	2.5 db±1 db
Carrier Power	96 mw±7 mw(+19.8 dbm ±0.3 db)
Subcarrier Power, Channel No. 1	14 mw±1.5 mw(+11.5 dbm ±0.5 db)
Subcarrier Power, Channel No. 2	14 mw±1.5 mw(+11.5 dbm ±0.5 db)
Subcarrier Power, Channel No. 3	36 mw±4 mw(+15.5 dbm ±0.5 db)
Space Loss at 250,000 Miles	204.5 db
Ground Antenna Gain	41.8 db
Transmission Line Loss	0.7 db
Receiver Noise Figure	7.5 db
Receiver Bandwidth ($2B_{L_0}$) at Receiver Threshold	20 cps
Receiver Threshold	−154.1 dbm
Angle Track Loop BW ($2B_L$)	0.06 cps
Angle Track Loop Receiver Threshold	−179.3 dbm
AGC Loop BW ($2B_{L_0}$) at Receiver Threshold	0.025 cps
AGC Loop Threshold	−183.1 dbm
At 250,000 Miles	
Received RF Signal Level	−141.1 dbm
S/N for RF Loop	8.0 db
S/N for AGC Loop	39.7 db
S/N for Angle Tracking Loop	38.2 db

III. DESIGN OF TRACKING RECEIVER

The specifications for the TRAC(E) tracking receiver for Pioneers III and IV are shown in the Appendix. Reference is made to the literature[2,6,7–10] with regard to the development of these specifications. The 20-cps RF phase-locked loop noise bandwidth at threshold is determined by the stability of the transmitter and receiver oscillators. As a consequence, the sensitivity of the receiving system is limited by the threshold of the RF phase-locked loop. With an effective noise temperature (T_{eff}) of 1435°K resulting from a receiver noise figure of 7.5 db, an apparent antenna noise temperature of 42°K and an 0.7-db loss for the simultaneous lobing RF bridge and antenna transmission line to the receiver input, the threshold of the receiver is −154.1 dbm. This assumes that the antenna is looking at a low-noise region of the sky.

The AGC system has a closed-loop noise bandwidth of 0.025 cps at receiver threshold. With this noise bandwidth, spin rate and spin modulation depth for the lunar probe are measured as an error signal in the AGC loop. In addition, rms gain error is maintained to 0.1 db at receiver threshold.

Gain and phase tracking in the angle tracking receiver relative to the reference receiver is ±2 db and ±10°, respectively, for input signal levels from −45 dbm to threshold. Gain tracking maintains near-constant gain in the hour angle and declination servosystems. Phase tracking maintains shift in the electrical axis of the antenna system (due to phase shift) to ±0.01 angular mils (±0.0006°) for a 1° antenna error pattern s-curve with a 40-db null depth. The 0.06-cps closed-loop noise bandwidth for the angle tracking servo-system shown in Table II maintains rms angle jitter to 0.4 angular mils (0.022°) at receiver threshold.

IV. DESCRIPTION OF EQUIPMENT

Probe Transmitter

The transmitter for the Pioneer IV probe was located in the central 6-inch diameter well of the instrumented payload (see Fig. 2). Fig. 3 shows the flight transmitter mounted on the webbed platform that forms part of the payload structure and also supports the shutter experiment. Transistorized subassemblies are mounted on micarta disks, interposed between the webbing to provide thermal isolation. The vacuum-tube cavity is fastened directly to the center web so that the whole payload becomes a heat sink for the vacuum tube. The overall weight of the platform and transmitter is 1.33 pounds. The transmitter less platform weighs 0.98 pound.

Circuit design was concentrated principally in the areas that would insure early completion of a 960-mc transmitter having the objective specifications outlined in Table III. Some of the specialized components and their features that helped make an efficient 960-mc lunar-probe transmitter possible are: 1) the Western Electric GF 45021 transistor, with its ability to operate efficiently at VHF frequencies (100 to 300 mc) previously restricted to subminiature tubes; 2) the GE-7077, a subminiature ceramic UHF triode, which permitted the design of efficient, subminiature UHF cavity amplifiers; 3) the Bell Telephone Laboratories' "Varactor," a silicon junction reactance diode developed for the U. S. Army Research and Development Laboratories, that operates as a frequency multiplier with considerably higher conversion efficiency than conventional diodes;

[7] W. K. Victor, "The Evaluation of Phase-Stable Oscillators for Coherent Communication Systems," Jet Propulsion Lab., California Institute of Technology, Pasadena, External Publication No. 337; May 8, 1956.

[8] A. J. Viterbi, "Design Techniques for Space Television," Jet Propulsion Lab., California Institute of Technology, Pasadena, External Publication No. 623; April 13, 1959.

[9] W. B. Davenport, Jr., "Signal-to-noise ratios in band-pass limiters," *J. Appl. Phys.*, vol. 24, pp. 720–727; June, 1953.

[10] W. K. Victor and M. H. Brockman, "The application of linear servo theory to the design of AGC loops," PROC. IRE, vol. 48, pp. 234–238; February, 1960.

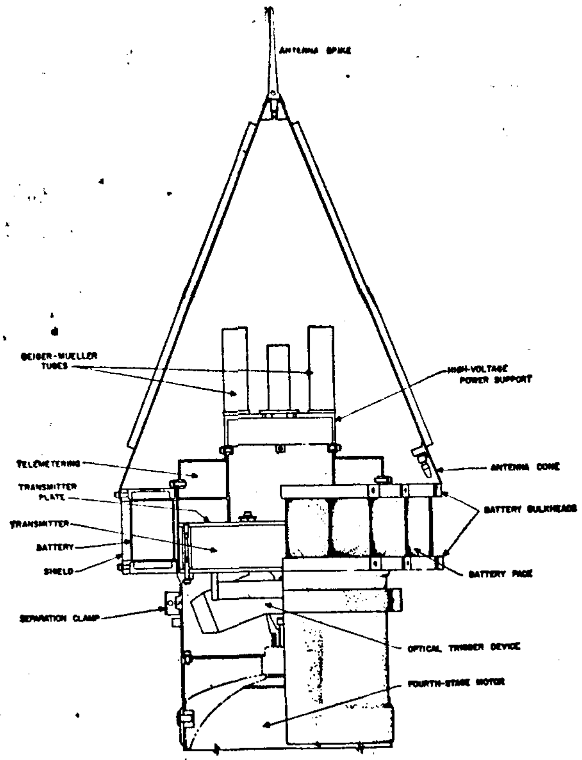


Fig. 2—Sketch of the Pioneer IV instrumented payload.

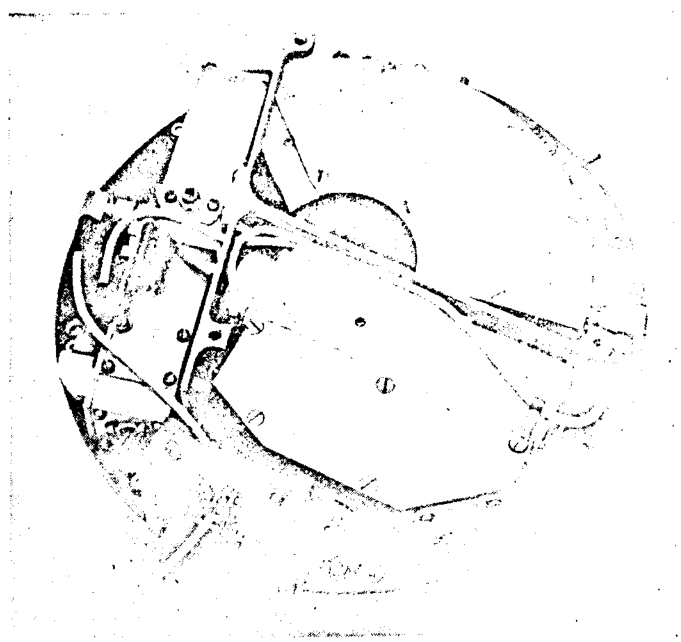


Fig. 3—Probe transmitter mounted on the webbed platform.

TABLE III
PROBE TRANSMITTER OBJECTIVE SPECIFICATIONS

Carrier frequency (nominal)	960 mc
Output power	180 mw
Crystal oscillator frequency (nominal)	40 mc
Short-term frequency stability—15 minutes	1 part 10^7
Long-term frequency stability	1 part 10^6
Power output stability	$\pm\frac{1}{2}$ db
Maximum incidental phase modulation	2 degrees per g
Over-all weight	0.9 pound
Over-all size 6-inches diameter $\times$ 1-inch height	28 inches^3
Primary power input	2.4 watts
Operating time with 6.5-pound battery	120 hours
Transmitter efficiency, exclusive of antenna gain	7.5 per cent

4) the ruggedized quartz crystal developed by the U. S. Army Signal Engineering Laboratories that enables phase-stable signals to be generated under conditions of extreme vibration; and 5) the development of reliable voltage-sensitive capacitors which simplify the design of the phase-modulation circuits.

Semiconductor devices operating in circuits from 40 to 960 mc provided the RF signal drive to the vacuum-tube power-amplifier which provided RF excitation to the probe antenna. The objective specifications of the probe transmitter (Table III) were achieved in the Pioneers III and IV experiments. The probe transmitter is described in detail in the literature.[11]

[11] L. R. Malling, "A 960-MC Lunar Transmitter," Jet Propulsion Laboratory, California Institute of Technology, Pasadena, External Publication No. 596; January 7, 1959.

Ground Tracking Receiver (*Goldstone Station*)

The RF portion of the TRAC(E) receiving system is mounted in an electronics enclosure on the rear portion of the antenna reflector structure[1] (see Fig. 4). The UHF portions of the reference, hour angle and declination angle receiver channels which include three preselector cavities, three balanced mixers and three 30-mc IF amplifiers, is housed in a weatherproof enclosure (see Fig. 5). The UHF portion of the local oscillator system which includes a $\times 6$ frequency multiplier, a three-way power divider, three UHF attenuators for local oscillator drive adjustment, and a crystal current meter circuit is mounted in a second weatherproof enclosure. Other weatherproof enclosures (see Fig. 5) contain power supplies and test equipment. The test equipment, which includes UHF and VHF signal generators and a noise-figure test setup, facilitates periodic checks of the receiver RF circuitry to insure optimum performance.

The amplified 30-mc output signals from the reference, hour angle and declination angle channels are transmitted from the electronics enclosure through coaxial cables to the receiver rack in the control building. The receiver rack comprises three cabinets containing the remainder of the receiving system, power supplies, and associated instrumentation (Fig. 6). The receiver system can be operated with a closed-loop RF bandwidth of either 20 or 60 cps which can be selected by means of a switch. Another switch permits selection of either an 11-second or a 300-second time constant filter for the AGC circuit. The system was operated in the 20-cps bandwidth and 300-second AGC filter time constant mode for the Pioneer IV experiment (Table II).

Operational control of the tracking system during a tracking operation is provided at the control console (Fig. 7). Control of both the tracking receiver and antenna servosystem is provided at the console. In general, the receiver and servosystems each have three basic modes of operation—manual, automatic track, and acquisition. In the acquisition mode, the tracking receiver and antenna search in frequency and angle, respectively, about the predicted frequency and angular position. Following acquisition, the received signal is automatically tracked in frequency and angular position.[12] Various receiver monitoring functions are provided at the control console.

[12] M. Eimer and R. Stevens, "Tracking and Data Handling for the Pioneer III and Pioneer IV Firings," Jet Propulsion Laboratory, California Institute of Technology, Pasadena, External Publication No. 701; August 14, 1959.

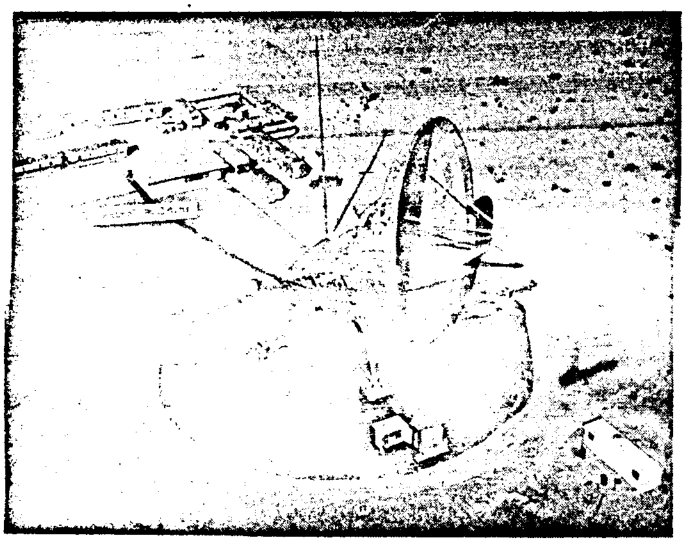


Fig. 4—Goldstone tracking station.

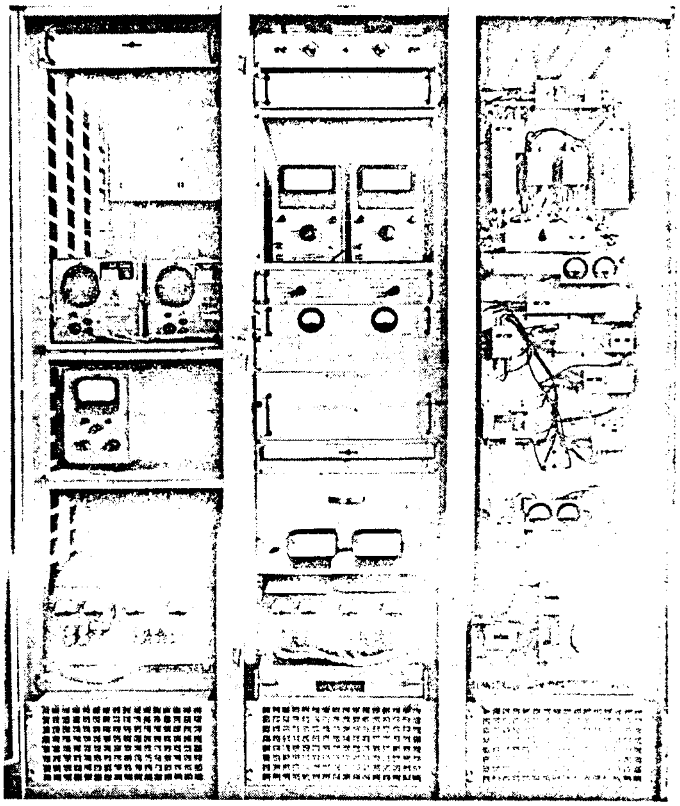


Fig. 6—Receiver rack.

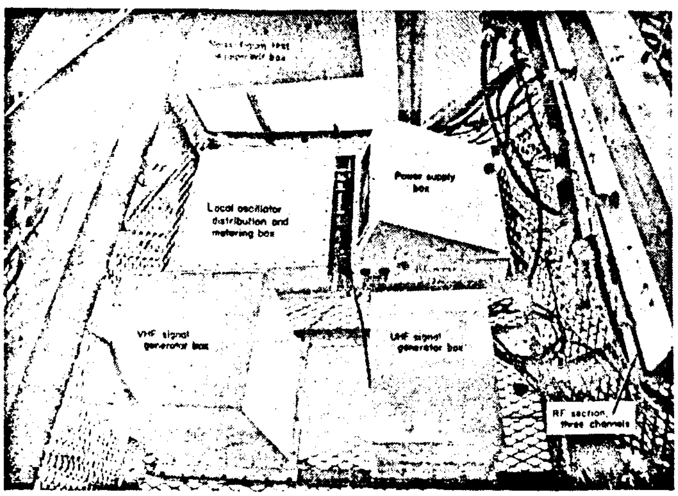


Fig. 5—Electronics enclosure.

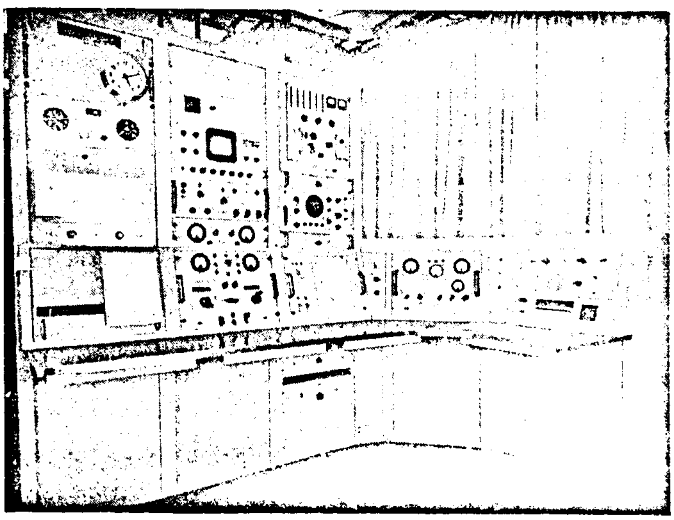


Fig. 7—Control console.

V. Performance Data for Pioneer IV Lunar Probe

Description of Pioneer IV Tracking

Following successful launching of Pioneer IV lunar probe at 05:10:56 GMT on March 3, 1959, radio tracking was accomplished through launch, injection, and coasting flight by the three JPL-operated stations (Cape Canaveral, Puerto Rico and Goldstone) out to a maximum range of 652,000 km (about 407,000 miles). At this range, after 82 hours and 4 minutes of flight, a rapid decrease in signal level occurred, as expected, due to loss of battery power. Prior to this event, received signal level was 5 db above threshold in a 20-cps bandwidth. After loss of signal during the fourth tracking period, a narrower bandwidth filter (10 cps) was installed in the tracking receiver, and the RF carrier was tracked for about 9 additional minutes. Had the batteries lasted, tracking could have been accomplished to a range of 1,850,000 km (1,150,000 miles) using the 10-cps filter.

Performance of the TRAC(E) tracking and communication equipment was highly satisfactory during this experiment. Performance data for the Goldstone Station are presented in the following material.

Received Signal Level and Spin Modulation: The noise figures of the Goldstone receiver based on data taken March 1 and 3, 1959, were as follows:

Reference Channel	7.5 db,
Hour Angle Channel	7.15 db,
Declination Channel	7.25 db.

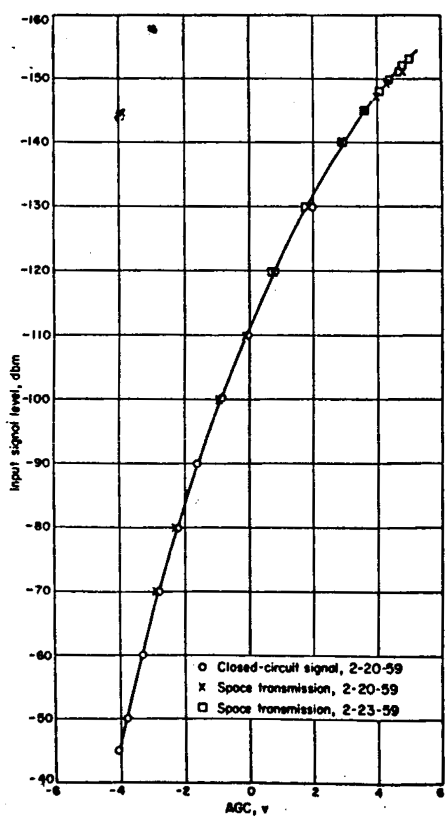
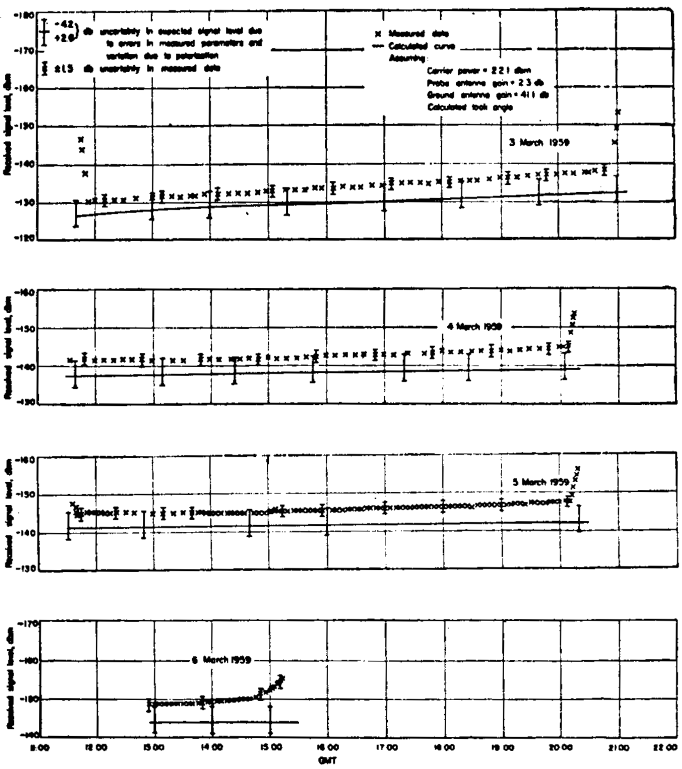


Fig. 8—Receiver sensitivity.

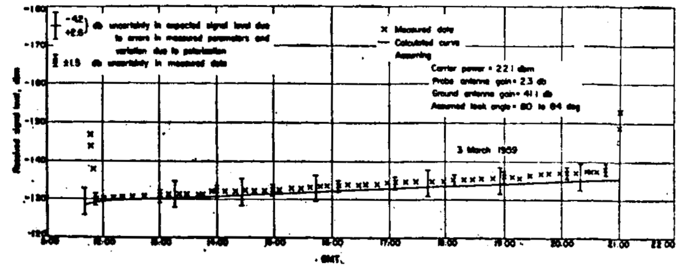
The measured noise figure of the reference channel agreed with the nominal value of 7.5 db. The theoretical receiving system sensitivity based on unity signal-to-noise ratio in a 20-cps bandwidth, a receiver noise figure of 7.5 db (effective noise temperature 1355°K), an apparent antenna noise temperature of 42°K and a total loss of 0.7 db for the antenna simultaneous lobing bridge system and transmission line to the receiver input is -154.1 dbm. The measured receiver sensitivity curve is shown in Fig. 8.

A comparison of measured with calculated signal level is shown in Fig. 9(a) for each tracking period for the Pioneer IV experiment. Throughout the tracking operation, the measured values are 3 to 5 db less than the calculated curves (based on nominal values and assumed vehicle attitude).

After despin at 16:32:24 GMT on March 3, the amplitude modulation of the signal resulting from spin and precession occurred at frequencies of 0.23 cps and 0.046



(a)



(b)

Fig. 9—Comparison of measured and calculated values of received signal level.

TABLE IV

RANGE AND SIGNAL LEVEL DATA FOR PIONEER IV

Tracking Period No.	Date	Time	Range Kilometers	Signal Level at Acquisition dbm	Signal Level at Loss of Lock dbm	Change of Signal Level (Neglecting Horizon Effect)	
						Measured db	Expected db
1	March 3, 1959	11:47:00 to 21:05:48	97,400 to 194,000	−144.5	−154.5	7.5	6.1
2	March 4, 1959	12:33:54 to 21:15:53	315,000 to 380,000	−141.5	−154.0	2.5	1.7
3	March 5, 1959	12:34:52 to 21:18:46	487,000 to 545,000	−147.5	−156.5	2.0	1.0
4	March 6, 1959	12:50:00 to 15:16:19	644,000 to 657,000	−150.5	−156.2	0.7	0.2

cps with a maximum modulation depth of 3 to 3.5 db and a minimum depth of 1 to 1.5 db. If the look angle between the spin axis and the line-of-sight to the probe is assumed to be 80° with a precession angle of 10°, the antenna pattern measurements agree with the observed depth of spin modulation, and the average signal strength comparison would appear as shown in Fig. 9(b) for the first tracking period.

The received signal levels were determined by measuring the AGC voltage with a digital voltmeter and converting this to signal level, using the receiver sensitivity curve (see Fig. 8). The measured values are indicated by the symbols in Fig. 9. In general, the slopes of the measured curves are slightly greater than the expected slopes. The signal levels at acquisition and loss of signal and the changes in level for each period are shown in Table IV. The estimated uncertainty of ±1.5 db in the measured data is based upon the following:

Receiver sensitivity error	±1 db,
Recording, calibration, and data reduction errors	±0.5 db.

In Fig. 9 the expected signal level is shown for comparison with the measured data. The solid line represents the signal level calculated on the basis of the following:

Transmitted carrier power	22.1 dbm
Vehicle antenna gain	function of look angle (see Fig. 10)
Ground antenna gain	41.1 db (indirect measurement)
Space attenuation (db)	92.1 + 20 $\log_{10}$ (range in kilometers).

The look angle is calculated on the assumption that the spin axis of the probe is essentially colinear with the velocity vector at injection (look angle varies from 45.5 to 56.2° for the experiment). The vehicle antenna pattern of Fig. 10 is based upon the measurements of antenna gain as a function of look angle and rotation of the antenna. The solid curve which was used for calculating signal level represents the geometric mean of the gain for full rotation at the given look angle. The dashed curves show the maximum and minimum gain and indicate the degree of amplitude modulation to be

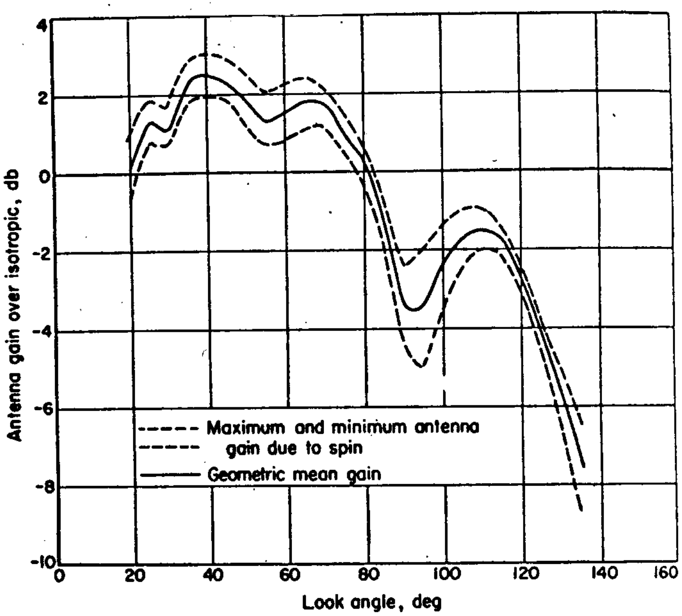


Fig. 10—Vehicle antenna pattern.

expected at each given look angle. The uncertainty of the calculated data is based upon the following:

Ground antenna gain (variation due to polarization	$\left.\begin{matrix}-1.7\\+0.1\end{matrix}\right\}$ db
Ground antenna gain (uncertainty)	±1 db
Transmitter power	±0.5
Vehicle antenna gain	±1.0
This gives a total uncertainty in the calculated data of	$\left.\begin{matrix}-4.2\\+2.6\end{matrix}\right\}$ db.

The measured signal levels are less than the expected values by 3 to 5 db. While the regions of uncertainty of the calculated and observed data overlap slightly, it is believed that the difference between expected and measured values is of the order of 3 db. This apparent loss of signal can be explained by assuming a look angle of the order of 80°.

Angle Tracking System: The reduction of tracking data was essentially a problem of filtering, by statistical analysis, the random observational errors and the sys-

TABLE V
LONG-TERM SYSTEM CAPABILITIES

Characteristic	Capability		
	1958	1960	1962
Transmitter Power	0.2 watt	10 watts	100 watts
Vehicle Antenna Gain	0 db	16 db	36 db
Receiver Sensitivity:			
Noise temperature	2000° K	400° K	40° K
Bandwidth	30 cps	30 cps	30 cps
Earth-vehicle range for 10-db S/N ratio	4×10^6 miles	4×10^7 miles	4×10^9 miles

tematic bias errors. The computational program for generating the Pioneer IV trajectory is described in detail in a JPL external publication.[12] The trajectory angles were corrected for atmosphere refraction and all known mechanical sources of error then compared with unsmoothed raw data for the last day of tracking (March 6, 1959). The hour angle errors for this period ranged from 0.035 to −0.11°. Near threshold, the hour angle errors were +0.02 to −0.1°. Using smoothed values of observed data, the hour angle error was about −0.03° at the system threshold. The declination errors for the same period ranged from +0.07° to −0.04°. Using smoothed values of observed data, the declination error was about 0.02° at threshold. As indicated in an earlier portion of this paper, calculated rms angle jitter at system threshold is 0.4 mil, which generally agrees with measured values.

VI. Future Plans for Improvement

Extra-terrestrial radio communications has been demonstrated and practiced successfully by radio astronomers for many years. As a result of their pioneering effort, the job of communicating with rocket-launched space probes has been and will continue to be much less difficult. Utilization of their data, analyses, techniques and in some cases actual equipment designs made it possible to develop the TRAC(E) system in a very short period of time with sufficient long-term capabilities that it could communicate to the distance of the moon in 1958 and to the planets during the period 1960–1962. (See Table V.) A basic element of the TRAC(E) system, for example, is the 85-foot diameter antenna designed for radio astronomy research by the Blaw-Knox Company under an Associated Universities contract. With this antenna and the TRAC(E) receiver described in this report, it would be possible to communicate to the nearby planets. However, future plans are to extend the range (and/or the bandwidth) still further by the addition of low-noise amplifiers. An over-all noise temperature of 400°K is predicted for 1960 using a parametric amplifier, and a temperature of 40°K for 1962 using a maser.

The real significance of Table V is that the principal factors which are expected to extend the communicating range are related to the space vehicle. Over a period of four years, it is suggested that the vehicle transmitter power could be increased 27 db, from 200 mw to 100 watts, and the vehicle antenna gain could be increased 36 db. With these improvements, Table V shows that space communications could be maintained anywhere in the solar system with a bandwidth of 30 cps. Solution of these problems in the time scale indicated depends on many factors, such as vehicle performance, payload weight, primary power, earth-seeking vehicle antenna system, financial support, etc.

The present TRAC(E) system is a one-way link which measures two angles and one-way Doppler, and receives telemetry. Future TRAC(E) communications will be two-way, employing a 10-kw UHF ground transmitter and vehicle-borne transponder. The two-way TRAC(E) system will measure two angles, range and range-rate; it will receive telemetry and also provide a radio command link to the space vehicle.

Appendix

TRAC(E) Tracking Receiver Design Specifications for Pioneers III and IV

I. Frequency—nominal 960.05 mc (also see XII).
II. Noise Figure—7.5 db or less.
III. Bandwidth—20 cps at threshold.
IV. Threshold—154.1 dbm defined as the signal level at which the receiver loses lock.
V. Range of Input Signal Level— −45 dbm to threshold.
VI. RF Loop Characteristics

A. RF Loop Transfer Function

$$H(s) = \frac{1 + \frac{3}{4B_L}s}{1 + \frac{3}{4B_L}s + \frac{9}{32B_L^2}s^2}$$

where

$$2B_L = \frac{1}{2\pi}\int_{-\infty}^{\infty} |H(j\omega)|^2 dw$$
$$= \frac{2}{3} B_{L_0}\left(1 + 2\frac{a}{a_0}\right)$$

and

$$2B_{L_0} = 2\left(\frac{9}{32}\frac{G_0}{\tau_1}\right)^{1/2}$$

$\tau_1 = R_1 C,$

G_0 = open-loop gain at threshold
$= 360 \times 30 \times k_m \times k_{vco} \times \alpha_0,$

k_m = sensitivity of the RF phase detector in volts/degree
$= 0.7$ volt/degree,

k_{vco} = sensitivity of the RF VCO in cps/volt
$= 250$ cps/volt,

α_0 = signal suppression factor at threshold
$= 0.088$ for 20-cps bandwidth.

$$\alpha = \left[\frac{1}{1 + \text{antilog}_{10}\left(\frac{1 + P_N - P_s}{10}\right)}\right]^{1/2}$$

$$= \left[\frac{1}{1 + \text{antilog}_{10}\left(\frac{1 - 134.1 - P_s}{10}\right)}\right]^{1/2}$$

where

P_N = available noise power in the 455-kc IF amplifier 2-kc pass band (expressed in dbm)

k = Boltzman's Constant, 1.37×10^{-23} joule/°K
$= \log_{10}(kT_{eff}\Delta f \times 10^3) = -134.1$ dbm

P_s = available signal power in the same 2-kc bandwidth in the same units as P_N.

Consequently

$$H(s) = \frac{1 + \frac{1}{\lambda}s}{1 + \frac{1}{\lambda}s + \frac{1}{2\lambda^2}s^2}$$

where

$$\lambda = \frac{4}{9} B_{L_0}\left[1 + \frac{2}{\alpha_0}\frac{1}{1 + \text{antilog}_{10}\left(\frac{1 - 134.1 - P_s}{10}\right)}\right]^{1/2}.$$

B. RF Loop Noise Bandwidth

1) Design Value at Design Threshold and Signal Frequency ($2B_{L_0} = 20$ cps)

2) Variation with Signal Level

The RF loop noise bandwidth shall vary from 20 cps at design threshold to 158 cps at strong signal levels ($\alpha = 1$).

3) Variation with Signal Frequency

The threshold RF loop noise bandwidth shall vary from 20 cps at design signal frequency to not less than 14.1 cps at signal frequencies displaced ± 2.6 parts in 10^5 from the design signal frequency.

C. RF Loop Phase Error

1) Variation with Signal Input Frequency

The static phase error at threshold shall not exceed 6° at signal frequencies displaced ± 2.75 parts in 10^6 from the design signal frequency. At these two frequency extremes, the threshold will be reduced 1 db from that specified at design signal frequency. Static phase error at strong signal levels ($\alpha = 1$) shall not exceed 13.5° at signal frequencies displaced ± 2.6 parts in 10^5 from the design signal frequency.

2) Maximum Rate of Change of Input Signal Frequency

The phase error at threshold shall not exceed 6° for a maximum rate of change of 6 parts in 10^9 per second in input signal frequency. At this maximum rate, the threshold will be reduced 1 db relative to that obtained for a zero rate of change in signal frequency.

The phase error at strong signals ($\alpha = 1$) shall not exceed 30° for a maximum rate of change of 3.5 parts in 10^7 per second in input signal frequency.

3) RMS Phase Error

The RMS phase error due to noise shall not exceed 1.0 radian at design threshold. The RMS phase error due to noise shall not exceed 0.06 radian at an input signal level of -120 dbm.

4) Residual Phase Error

The residual phase error shall not exceed 3° peak at strong signal levels ($\alpha = 1$) within an RF loop noise bandwidth of 20 cps.

5) Noise Bias

The maximum phase error due to noise at threshold shall not exceed 1 per cent of the phase detector S curve amplitude at threshold (equivalent to static phase error of 0.6°).

VII. AGC Loop Characteristics (Coherent AGC)

A. AGC Loop Transfer Function

$$H(s) = \frac{1}{\left(1 + \frac{1}{G}\right) + \frac{\tau}{G}s}$$

where

τ = time constant of AGC filter
$= 300$ seconds

G = gain of the AGC loop
$= K_D K_A$

and

K_D = AGC detector constant expressed in volts/db
$= 3.1$ volts/db at threshold
$= 4.0$ volts/db at -45 dbm input signal level

K_A = constant associated with the gain of the receiver expressed in db/volt
$= 5$ db/volt at threshold
$= 17$ db/volt at -45 dbm input signal level.

B. AGC Loop Noise Bandwidth

1) Design Value at Design Threshold
$2B_L = 0.025$ cps

2) Variation with Signal Level
The AGC loop noise bandwidth shall vary from 0.025 cps at design threshold to 0.11 cps at an input signal level of -45 dbm.

C. AGC Loop Gain Error

1) Static Gain Error
The variation in coherent detected receiver output shall vary not more than 6 db for the range of input signal levels from -45 dbm to threshold.

2) Maximum Rate of Change of Input Signal Level
The gain error at threshold shall not exceed 1 db for a maximum rate of change of 0.05 db per second in input signal level. The gain error at an input signal level of -45 dbm shall not exceed 1 db for a maximum rate of 0.25 db per second in input signal level.

3) RMS Gain Error
RMS gain error introduced in the RF and angle tracking loops at threshold shall not exceed 0.1 db rms. RMS gain error at an input signal level of -120 dbm shall not exceed 0.003 db rms.

VIII. 30/31-mc Frequency Shifter Phase-Locked Loop Characteristics

A. Frequency Shifter Loop Transfer Function

$$H(s) = \frac{1 + \dfrac{3}{4B_L} s}{1 + \dfrac{3}{4B_L} s + \dfrac{9}{32B_L^2} s^2}$$

where

$$2B_L = 2\left(\frac{9G_0}{32\tau_1}\right)^{1/2}$$

$\tau_1 = R_1C$
$G = 360 \times 32 \times k_m \times k_{vco}$
k_m = sensitivity of the frequency shifter phase detector in volts/degree
= 0.25 volt/degree
k_{vco} = sensitivity of the frequency shifter VCO in cps/volt
= 45 cps/volt.

B. Frequency Shifter Loop Noise Bandwidth

1) Design Value at Design Frequency
$2B_L = 1340$ cps

2) Variation with Frequency
The frequency shifter loop noise bandwidth shall vary from 1340 cps at design frequency to not less than 950 cps at frequencies displaced ± 3 parts in 10^5 from the design frequency.

C. Frequency Shifter Loop Phase Error

The static phase error shall not exceed 5° at frequencies displaced ± 3 parts in 10^5 from the design frequency.

IX. 30.455-mc SSB Modulator Phase-Locked Loop Characteristics

A. SSB Modulator Loop Transfer Function

$$H(s) = \frac{1 + \dfrac{3}{4B_L} S}{1 + \dfrac{3}{4B_L} S + \dfrac{9}{32B_L^2} S^2}$$

where

$2B_L = 2(9/32\ G/\tau_1)^{1/2}$
$\tau_1 = R_1C$
$G = 360 \times K_m \times K_{vco}$
K_m = sensitivity of the SSB modulator phase detector in volts/degree
= 0.7 volt/degree
K_{vco} = sensitivity of the SSB modulator VCO in cps/volt
= 250 cps/volt.

B. SSB Modulator Loop Noise Bandwidth

1) Design Value at Design Frequency
$2B_L = 1200$ cps

2) Variation with Frequency
The SSB modulator loop noise bandwidth shall vary from 1200 cps at design frequency to not less than 850 cps at frequencies displaced ± 3 parts in 10^5 from the design frequency.

C. SSB Modulator Loop Phase Error

The static phase error shall not exceed 10° at frequencies displaced ± 3 parts in 10^5 from the design frequency.

X. Angle Error Channel Characteristics

A. Gain Tracking

The differential gain between either angle error channel and the reference channel shall not exceed 2 db over the range of input signal levels from -45 dbm to threshold. Gain tracking is determined by comparison of the coherent output signal levels in the angle error channel to the reference channel output.

B. Phase Tracking

The differential phase between either angle error channel and the reference channel shall not exceed $\pm 10°$ over the range of input signal levels from -45 dbm to threshold. Phase tracking is determined by comparison of the phase of the coherent output signal level in the angle error channel to reference channel phase output.

C. RMS Angle Tracking Error

RMS angle tracking error in the 0.06 cps noise bandwidth of the angle tracking servosystem shall not exceed 0.022 rms at threshold.

XI. Modulation Characteristics

A. Amplitude Response and Phase Symmetry of 2-kc Pass Band

The amplitude characteristic of the 455-kc IF amplifier shall be flat to ± 1.5 db within the 2-kc pass band. The phase characteristic of the 455-kc IF amplifier shall be symmetrical to within 45° about the center of the 2-kc pass band.

XII. Frequency—The nominal center frequency shall be 960.05 mc with the ability to track plus or minus 3.0 parts in 10^5 from the nominal center frequency. By changing the crystal and retuning the VCO, the center frequency can be changed between 955 mc and 965 mc.

XIII. Input VSWR—The input VSWR to the receiver shall be less than 1.5 to 1 for a 50-ohm transmission line.

XIV. Image Rejection—The image rejection of the receiver shall be at least 40 db.

XV. Telemetry Bandwidth—The narrowest bandwidth of the receiver before the telemetry output shall be 10 kc.

XVI. Residual Phase Modulation—The residual phase modulation in the RF loop when measured with a signal source at -60 dbm shall be less than 3° peak.

XVII. Internal Interference in the RF Loop—The internal interference in the RF loop due to coherent leakage signals of the receiver shall be at least 40 db below the signal level at threshold when the interference enters ahead of the limiter and at least 60 db below the signal level at threshold when the interference enters following the limiter.

XVIII. Internal Interference in the AGC Loop—The internal interference in the AGC loop due to coherent leakage signals of the receiver shall be at least 40 db below the signal level at threshold.

XIX. Internal Interference in the Angle Detector Channels—The internal interference in the angle detector channels due to coherent leakage signals of the receiver shall be at least 40 db below the signal level at threshold.

XX. Cross Coupling Between Channels—The signal isolation between any two channels shall be at least 60 db.

XXI. Receiver IF Frequencies—The receiver IF frequencies shall be 30 mc and 455 kc.

XXII. First Local Oscillator Frequency—The first local oscillator signal shall be derived from a 31-mc VCO which is frequency multiplied by 30.

XXIII. Coherent Local Oscillator Frequencies—The local oscillator signals shall be derived in such a manner that the received signal frequency can be determined by measurement of the 31-mc VCO frequency only.

XXIV. Recording Outputs—Provision shall be made for making the following available for recording:

receiver AGC,
RF loop dynamic phase error and telemetry,
telemetry subcarriers,
Doppler frequency plus constant frequency,
spin modulation,
declination error,
hour angle error.

ACKNOWLEDGMENT

The authors wish to acknowledge the efforts of all the Jet Propulsion Laboratory personnel whose teamwork contributed to successful radio frequency tracking and communication with the Pioneers III and IV space probes. They wish to express particular thanks to Dr. E. Rechtin and W. K. Victor of JPL under whose direction this effort was accomplished. Acknowledgment is also made to the Collins Radio Company, Cedar Rapids, Iowa, who provided assistance during the design, construction, and installation of the Goldstone Radio Tracking System.